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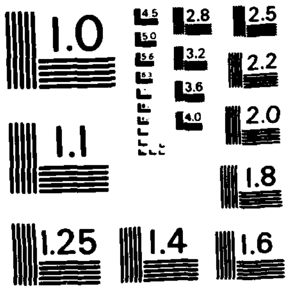

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UPPER-ATMOSPHERE FEATURES REVEALED BY THE ORBIT OF 1980-43A

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SUMMARY

The satellite NOAA-B (1980-43A) was launched in May 1980 into an orbit with perigee height near 260 km and apogee height 1440 km, at an inclination of 92.2°. The lifetime was 11 months. The orbit has been determined at 40 epochs between October 1980 and May 1981 from about 3000 radar and optical observations. The average orbital accuracy, radial and cross-track, was about 100 m, with rather better accuracy in the final 14 days.

The variation of orbital inclination has been analysed to determine two good values of atmospheric rotation rate, namely 1.10 ± 0.10 rev/day at 300 km (average local time) and 1.15 ± 0.06 rev/day at 225 km (evening).

The effect of atmospheric rotation on the precession of the orbital plane of an actual satellite has never previously been detected; it is clearly apparent for 1980-43A in its last days, and conforms to the expected theoretical change.

The variation of perigee height has been analysed to determine ten values of atmospheric density scale height, for heights of 280-370 km. These values, accurate to about 3%, exceed by 15% the values indicated by the *COSPAR International Reference Atmosphere*. Solar activity was higher in the years 1980-81 than at any time since early 1958, and it appears that the *CIRA* model underestimates the density and density scale height at high levels of solar activity.

Departmental Reference: Space 623

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1 INTRODUCTION

The meteorological satellite NOAA-B, designated 1980-43A, was launched on 29 May 1980 but failed to achieve its intended orbit and decayed within a year, on 3 May 1981[1]. The satellite was a rectangular box, 3.71 m long, 1.88 m in diameter and just over 1400 kg in weight, of which the fuel supply comprised almost half. Its initial perigee and apogee heights were 264 km and 1445 km, and the orbital inclination was 92.23°.

The orbit has been determined at 40 epochs from about 3000 radar and optical observations using the RAE orbit refinement program PROP in the PROP 6 version[2]; orbits were determined for each of the 14 days prior to decay when a large number of observations by the assigned and contributing sensors of the North American Air Defense Command (NORAD) were made available to us.

The main purpose of this Report was to evaluate the atmospheric rotation rate from changes in the satellite's orbital inclination. This was successfully accomplished and it was also possible to make two other useful analyses: the right ascension of the node was analysed to demonstrate for the first time the effects of atmospheric rotation on this orbital element; also, since the solar activity was at a higher level than at any time since 1958, the values of scale height derived from the decrease in perigee height proved to be of unexpected significance.

2 ORBIT DETERMINATION

2.1 Observations

The orbit of 1980-43A has been determined at 40 epochs from 12 October 1980 until its decay. The observations accepted in the final orbits numbered 2789, consisting of over 1250 US Navy Navspasur observations supplied by the Naval Research Laboratory, nearly 1100 NORAD observations, over 250 British radar, 168 visual observations from volunteer observers reporting to the University of Aston and 12 from the kinetheodolite at the South African Astronomical Observatory.

2.2 Observational accuracy

The observational accuracy of the US Navy and optical observing stations with 4 or more observations accepted is indicated in Table 1 in the form of rms residuals, obtained using the RAE computer program ORES[3].

Table 1

Residuals for selected stations

Station		Number of observations	Rms residuals			
			Range	Minutes of arc		
			km	RA	Dec	Total
1	US Navy	187		2.3	2.6	3.4
2	US Navy	165		3.0	2.9	4.2
3	US Navy	185		2.8	3.0	4.1
4	US Navy	172		2.8	2.7	3.8
5	US Navy	193		2.3	2.7	3.5
6	US Navy	196		3.2	2.9	4.3
29	US Navy	160	0.8	0.4*	0.9*	
2125	Street	4		1.7	1.9	2.5
2265	Farnham	5		3.9	4.0	5.6
2414	Bournemouth	60		3.0	4.2	5.2
2418	Sunningdale	4		3.3	2.5	4.1
2420	Willowbrae	78		2.3	2.0	3.0
2431	Copthorne	4		0.7	0.7	1.0
2572	Wittenheim	4		3.2	5.0	6.0
2577	Cape Kinetheodolite	12		0.58	0.65	0.87

*Geocentric

The residuals represent the sum of the observational errors and orbital errors. Since the drag was severe and variable, the orbital errors may occasionally be important. Certainly the residuals for both the US Navy and optical observations are slightly larger than usual, and this seems the most likely explanation.

The satellite's orbit was nearly sun-synchronous and this led to long intervals of invisibility, thus reducing the number of visual observations. As in many previous orbit determinations, the observations from Willowbrae (R.D. Eberst) and Bournemouth (D.J. Hopkins) made up a very large proportion of the visual observations.

2.3 Orbital elements and accuracy

The computed sets of orbital elements with their standard deviations at each of the 40 epochs are listed in Table 2. The epoch for each orbit is at

00 hours on the day indicated and the PROP program fits the mean anomaly M by a polynomial of the form

$$M = M_0 + M_1 t + M_2 t^2 + M_3 t^3 + M_4 t^4 + M_5 t^5 \quad , \tag{1}$$

where t is the time measured from epoch and the number of M-coefficients used depends on the drag experienced by the satellite at around that epoch. For 1980-43A, the coefficients $M_0 - M_2$ were sufficient for just 3 of the 40 orbits, 15 orbits required M_3 to be added, 16 orbits needed M_4 and 6 orbits required the full complement of $M_0 - M_5$. The measure of fit, shown by ε, varied between 0.30 and 1.36 with an average value of 0.67, indicating that the observations were fitted well on most of the orbits.

The values of inclination, i, plotted in Fig 1, had standard deviations between 0.0004° and 0.0024°, the average being 0.0012°, corresponding to about 140 m in distance. For the final 14 daily orbits, the sd varied from 0.0004° to 0.0016° (the latter on the date of decay), with an average of 0.0007°. The right ascension of the node, Ω, had standard deviations 20% lower than i, on average.

For eccentricity, e, the sd ranged between 4×10^{-6} and 3×10^{-5}, with an rms of 1.4×10^{-5} or 100 m in distance, while the rms value for the final 14 orbits was 1×10^{-5} (70 m). The values of $a(1 - e)$ from Table 2 are plotted in Fig 2. They show the expected oscillation due to odd zonal harmonics, of amplitude about 10 km, and the general decrease due to drag as the lifetime progresses.

Fig 3 shows the values of M_2, which is proportional to the drag acting on the satellite. There are many irregular variations, which reflect the response of air density to the high and variable solar activity prevailing in the solar-maximum period of 1980-81. Underlying the irregular changes is a smoother variation influenced by the oscillations in perigee height, particularly the final steep decrease after MJD 44680. Changes in M_2 may also have occurred because of changes in the satellite's cross-sectional area.

3 ZONAL WINDS FROM ANALYSIS OF INCLINATION

3.1 Introduction

The decrease of inclination during the satellite's life, visible in Fig 1, is caused mainly by the aerodynamic forces normal to the orbital plane, created by atmospheric rotation. If other perturbations are removed, the decrease in i can be analysed to determine the atmospheric rotation rate, which gives the zonal (west-to-east) wind.

3.2 Removal of perturbations

The lunisolar and zonal harmonic perturbations have been calculated using the computer program PROD[4], and the perturbations due to the $J_{2,2}$ tesseral harmonic are given with the PROP printout. Removal of these sources of perturbation gives the values of inclination plotted in Fig 4.

There are further perturbations in inclination due to earth and ocean tides, and the change in reference system produced by the precession of the Earth's axis. The magnitude of these perturbations for polar orbits is indicated in Ref 5: the largest earth-tide effect is that of lunar origin, which can change the inclination by as much as 0.0002° per 100 days; this effect is negligible here, since the smallest standard deviation in inclination, in the first 190 days is 0.0007°. The correction to i required as a result of precession is given approximately by[2]

$$\Delta i_{PREC} = \frac{8.7 \times 10^{-4}}{\dot{\Omega}} (\cos \Omega - \cos \Omega_1) \quad \text{degrees} \qquad (2)$$

where Ω_1 and Ω are the final and current values of Ω, and $\dot{\Omega}$ is in degrees/day. Here $\dot{\Omega} \approx 0.28$ deg/day, so the numerical factor in (2) is 3.1×10^{-3}. During the last 14 days of the satellite's life $\Delta i_{PREC} < 0.0001°$ and is negligible. During the first 190 days the maximum value of $|\cos \Omega - \cos \Omega_1|$ is 0.17, so that $\Delta i_{PREC} < 0.0005°$, and this is also negligible, since the average sd of the values of i in the first 190 days is 0.0012°.

Perturbations due to meridional winds are negligible because the inclination is so close to 90°.

Perturbations due to resonance with the Earth's gravitational field may be significant, and will be discussed in section 3.3.2.

3.3 Analysis

3.3.1 Between 12 October 1980 and 19 February 1981

The theoretical variation of i with time for a series of values of atmospheric rotation rate Λ, was obtained using the ROTATM computer program, and the value of $\Lambda = 1.10$ rev/day best fits the observed points on orbits 1-19, between 12 October 1980 and 19 February 1981, as shown in Fig 4.

As the scale at the top indicates, the local time at perigee is initially at 08-09 h, then jumps by 10 hours as perigee passes near the south pole on 3 November, and remains near 17-18 h until 25 December, when perigee passes near

the north pole and the local time shifts to 03-04 h until mid-February 1981. It is usually helpful[6] to classify the values of Λ obtained from orbit analysis according to their local time in one of three categories, namely, morning (06-12 h), evening (18-24 h) or average. This first value of Λ obtained here is obviously not biased towards either morning or evening, and falls into the 'average' category. Since the perigee moves from high southerly latitudes across the equator to the north pole and back again, between October and February, there is no significant seasonal bias.

As all the 19 points are less than 0.0024° from the curve, it is reasonable to assign a standard deviation of 0.0012° to the curve, and so the total decrease in inclination, namely 0.019°, is likely to be measured with an error of about $\sqrt{2} \times 0.0012°$, that is 0.0017° or 9%. Thus the appropriate accuracy for Λ is 1.10 ± 0.10.

The average perigee height during this time is 260 km, and the height at which the value of Λ applies may be taken as $\frac{3}{4}H$ above this, where the density scale height H is about 55 km. So, the final result is:

$\Lambda = 1.10 \pm 0.10$ for 300 km height, average local time and average season.

3.3.2 Between 19 February and 2 April 1981

The satellite experienced 15th-order resonance with the Earth's gravitational field on 4 March 1981. Because of the high drag at this time, the passage through resonance was rapid, but the resulting perturbation still seemed likely to be appreciable.

So an extra orbit was determined for 5 March 1981 and further orbits were determined by PROP for epochs two days before and after this orbit and before and after orbits 20, 21 and 22, and three days after orbit 19, to give a total of 14 orbits during the period when the inclination was likely to be affected by resonance. The change in inclination due to resonance was then calculated using the THROE computer program with values for lumped harmonics taken from Ref 7, namely:

$$\left.\begin{array}{llll} 10^9\bar{C}_{15}^{0,1} = -16.8 & \qquad & 10^9\bar{S}_{15}^{0,1} = -5.4 \\ 10^9\bar{C}_{15}^{-1,2} = -52 & \qquad & 10^9\bar{S}_{15}^{-1,2} = -42 \end{array}\right\} . \qquad (3)$$

The effects of the $(\bar{C},\bar{S})^{1,0}$ coefficients are negligible at this inclination.

The resulting variation of i due to resonance is shown in Fig 5, where the initial value of i is arbitrary and only the change in i is of interest.

The pre-resonance oscillation in Fig 5 is centred on a value close to 92.1931° and the post-resonance oscillation is centred on a value close to 92.1961°, so that the resonance produces an increase of 0.0030° in i .

The overall variation in i , shown as a broken line in Fig 4, has been calculated by adding (i - 92.1931) from Fig 5 to the values given by ROTATM, the value of Λ in ROTATM (0.825) being chosen to bring the curve to the correct value for the start of the final section, from 2 April 1981 onwards, namely i = 92.1787.

The value of 0.825 required for Λ is not accurate enough to qualify as a 'determination' of Λ , since it has a standard deviation of about 0.15. As the local time at perigee is 12-13 h, there is a bias towards morning (06-12 h) when, according to Ref 6, a value of Λ near 0.85 would be expected, for height 280 km and average season.

In view of the high drag, the change in inclination due to the 15th-order harmonics in the geopotential is surprisingly large, and it is clear from the form of Fig 5 that nearly the largest possible increase has happened to occur. The perturbation at the 31:2 resonance (13 April) should, under the usual assumption of proportionality to M_2 , be less than one tenth of that at 15th-order resonance, that is, less than 0.0003° and hence negligible. The 29:2 resonance occurs in October 1980 between orbit 2 and orbit 3, and on the same assumptions could produce a maximum change in inclination of 0.0007°. This cannot be regarded as important, because the accuracy of the curve at this time has been estimated as 0.0012°; but if a net decrease of 0.0007° did occur at 29:2 resonance, the first two points in Fig 4 would fit better. Good values for lumped coefficients of order 29 are not available, so the change cannot be reliably calculated.

3.3.3 Between 2 April 1981 and decay (3 May 1981)

Fig 6 shows the values of inclination and the fitted Λ curve in the final phase of the satellite's life. (The curve is also given in Fig 4 on a smaller scale.) The value of Λ required is 1.15. The fitting is reasonably good, and there is no obvious break-point such that a better fitting could be achieved by using two different values of Λ . The standard deviation in Λ is difficult to estimate, because the values of inclination at the beginning and end are less accurate than the intermediate values. If we assign an error of 0.002° at the beginning and 0.001° at 2 May, the sd in Λ is 0.06 since the total decrease in inclination is 0.042°. Alternatively, an error of 0.001° might be assigned between 20 April and 2 May, where the decrease in inclination

is 0.0275°; this also gives the sd of Λ as 0.06. So we quote $\Lambda = 1.15 \pm 0.06$.

Fig 4 shows that the local time at perigee is between 22 and 24 h, so the value of Λ is in the 'evening' category of Ref 6. Since perigee moves from latitude 88° north on 2 April to 45° south on 3 May, the season is 'average'. The perigee height decreases from 220 km on 20 April to 182 km on 2 May (the time interval where there are accurate daily values), so the average perigee height is about 200 km, and the height at which Λ applies is about 225 km. Thus we have:

$\Lambda = 1.15 \pm 0.06$ for 225 km height, evening and average season.

4 ANALYSIS OF RIGHT ASCENSION

4.1 Introduction

The aerodynamic force produced by atmospheric rotation causes perturbations in the right ascension of the ascending node Ω, as well as in the inclination. However, these atmospheric perturbations in Ω are usually very small and they cancel out during each half cycle of the argument of perigee ω. Consequently, the atmospheric effect on right ascension has never been conclusively demonstrated. The orbit of 1980-43A in its last few days offers some hope of successful analysis of Ω, and this possibility is pursued below.

4.2 The effect of atmospheric rotation on Ω

The change in Ω due to an atmosphere rotating at a rate Λ is given by[8]

$$\Delta\Omega = \frac{\Lambda \sin 2\omega}{6\sqrt{F}}\left(\frac{I_2}{I_0}\right)\left\{1 - 2e\left(\frac{I_1}{I_2} + \frac{I_1}{I_0}\right) + c\left(\frac{I_4}{I_2} - \frac{I_2}{I_0}\right)\cos 2\omega + O(c^2, e^2)\right\}\Delta T , \quad (4)$$

where I_n is the Bessel function of the first kind and imaginary argument, of argument $z = ae/H$; $\sqrt{F}$ is a factor which has a value 1.00 for 1980-43A; and ΔT is the change in orbital period expressed in days. The parameter c expresses the effects of atmospheric oblateness ε', being given by $c = \{\varepsilon' a(1 - e) \sin^2 i\}/2H$.

For most satellites Ω changes rapidly, at a rate of several degrees per day, as a result of the gravitational forces produced by the departure of the geopotential from spherical symmetry. For 1980-43A, however, which is a near-polar orbit, the rate is only 0.3° per day and there is hope of removing this perturbation without significant error.

If a measurable change in Ω is to build up, it is obvious from equation (4) that there must be a large change ΔT in the orbital period, while $\sin 2\omega$

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retains the same sign. For 1980-43A, the most promising time interval is the last 8 days of the life, where the largest change ΔT occurs and $\sin 2\omega$ is consistently negative (see Table 2).

4.3 Procedure for removal of perturbations

The terrestrial gravitational perturbations in Ω were calculated at daily intervals, with a re-start each day, using the computer program PROD and harmonics up to degree 20. Since PROD does not include the effects of drag, this procedure gives 8 daily values of $\dot{\Omega}$ due to terrestrial gravity at dates April 26.0, 27.0 ... May 3.0. The first 7 of these were integrated with the Gregory central-difference formula for integration interval w,

$$\int_0^w \dot{\Omega} dt = w\left(\dot{\Omega}_{\frac{1}{2}} - \frac{1}{12}\delta^2\dot{\Omega}_{\frac{1}{2}} + \frac{11}{720}\delta^4\dot{\Omega}_{\frac{1}{2}} + \dots\right), \tag{5}$$

where $\dot{\Omega}_{\frac{1}{2}} = \frac{1}{2}(\dot{\Omega}_0 + \dot{\Omega}_w)$, $\Delta\dot{\Omega}_0 = \dot{\Omega}_w - \dot{\Omega}_0$, etc, $\delta^2\dot{\Omega}_{\frac{1}{2}} = \frac{1}{2}(\Delta^2\dot{\Omega}_{-w} + \Delta^2\dot{\Omega}_0)$, etc.

Here $w = 1$ and the δ^4 term is negligible. The running total of these integrals, which we denote by $\Delta\Omega_G$, gives the total perturbation to be subtracted from the PROP value of Ω (Table 2) in order to clear terrestrial gravitational perturbations.

Equation (5) cannot be applied between May 2.0 and 3.0, because $\ddot{\Omega} \to \infty$ early on May 3 and the central difference value becomes unreliable. So an analytical integration is necesary. If suffix 0 denotes values at May 2.0, the orbital period T at a later time is given by theory[8] as

$$\frac{T}{T_0} = 1 - \frac{3H}{2a} \ln \frac{z_0 I_1(z_0)}{z I_1(z)} . \tag{6}$$

Between May 2.0 and 3.0, the value of z decreases from about 1.4 to about 1.0, a region in which $I_1(z)$ is approximately proportional to $z^{1.1}$. Also the theory[8] indicates that $z^2/z_0^2 \simeq 1 - At$, where t is the time after May 2.0, and $1/A$ is approximately the lifetime after May 2.0. Thus equation (6) gives

$$\frac{T}{T_0} \simeq 1 - \frac{3H}{2a} \ln \left(\frac{z_0}{z}\right)^{2.1} \simeq 1 + \frac{3H}{2a} \ln (1 - At)^{1.05} . \tag{7}$$

The rate of change of Ω due to terrestrial gravity is proportional to $a^{-3.5}$ and hence to $T^{-7/3}$. Therefore

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$$\dot{\Omega} = K(T/T_0)^{-7/3} \simeq K\left\{1 - \frac{11H}{3a}\ln(1 - At)\right\} , \qquad (8)$$

where K is constant. The PROD output shows that $\dot{\Omega} = 0.3311$ deg/day at May 2.0 and 0.3393 deg/day at May 3.0. Substituting these values in equation (8), and taking $11H/3a$ as 0.016, we find $A = 0.788$. Hence the perturbation in Ω due to terrestrial gravity from May 2.0 to 3.0 is

$$\int_0^1 0.3311\{1 - 0.016 \ln(1 - 0.788t)\}dt = 0.3342° . \qquad (9)$$

The lunisolar perturbation to Ω was calculated by re-running the PROD program (with daily restart) with lunisolar perturbations included, and then subtracting the previous values with lunisolar terms absent. These accumulated lunisolar perturbations, $\Delta\Omega_{LS}$ say, were also subtracted from the original PROP values, Ω_{PROP}. Thus we arrive at a value Ω_2 free of terrestrial and lunisolar gravitational perturbations and given by

$$\Omega_2 = \Omega_{PROP} - \Delta\Omega_G - \Delta\Omega_{LS} .$$

4.4 Results

The values of Ω_2 are plotted in Fig 7 together with a curve giving the theoretical change due to an atmospnere rotating at 1.15 rev/day, the value appropriate for the last 7 days of the satellite's life (Fig 6). Although the total expected change in Ω due to atmospheric rotation during the 7 days is only 0.0028°, the values of Ω_2 and the curve are in good agreement, none of the points being more than 2 sd from the curve.

Thus, the change in Ω due to atmospheric rotation is consistent with an atmospheric rotation rate of $\Lambda = 1.15$. The values are not accurate enough to allow an independent determination of Λ of useful accuracy, but the agreement between theory and observation is close enough to justify the conclusion that the observational standard deviations are realistic and that the theory - which has not been previously tested against observation - is basically correct.

5 ANALYSIS OF PERIGEE HEIGHT

5.1 Determining density scale height: procedures and results

Fig 2 shows that the perigee distance $a(1 - e)$ suffers considerable purturbations due to the odd zonal harmonics in the geopotential, and smaller lunisolar gravitational perturbations. These have been removed using the PROD

computer program with daily integration steps and restarts at intervals of about 50 days, to give a perigee distance freed of gravitational perturbations. On subtracting the mean Earth radius, 6367 km, we obtain a perigee 'height' Q free of gravitational perturbations, plotted in Fig 8.

The values of Q in Fig 8 show a continual decrease due to the effects of air drag, and, if $z > 3$, the rate of decrease of Q in an atmosphere of ellipticity ε' may be expressed as[9]

$$\dot{Q} = -\frac{H_1\dot{M}_1}{3M_1 e}\left(1 - 2e + \frac{H}{4ae} - \frac{2\varepsilon'}{e}\sin^2 i \cos 2\omega\right) . \qquad (11)$$

If H_p denotes the value of the density scale height at perigee, the quantity H_1 in equation (11) is the value of density scale height at a height $\frac{3}{2}H_p$ above perigee.

Values of $\dot{Q}$ for use in equation (11) are found in the form $\Delta Q/\Delta t$, where the time interval Δt is chosen to be long enough to ensure that the change ΔQ in Q is large enough to be determined with a formal accuracy better than 3%. Since the standard deviations in the values of $a(1 - e)$ are of order 100 m, the value of ΔQ should be at least 3 km. The values of ΔQ are obtained from the mean curve in Fig 8, rather than the individual points. The values of $\dot{M}_1$, M_1, e and $\cos 2\omega$ for use in equation (11) are of course also averaged over the time interval Δt. This averaging should not lead to errors of more than 1%: the ε' term is normally small and this much reduces the effect of errors in averaging $\cos 2\omega$.

The use of equation (11) for calculating H_1 from the observational values of $\dot{Q}$, $\dot{M}_1$, M_1, e, etc has the advantage that it does not require any 'model atmosphere' to be specified. The only assumption is that the atmosphere is oblate, with the ellipticity ε' taken as 0.00335.

The values of H_1 obtained from equation (11) are shown in histogram form in Fig 9 as unbroken horizontal lines. For the last two values of H_1 in Fig 9, equation (11) is nearing the limits of its validity because $z = ae/H_p$ decreases to near 3, and a correction is needed. When $z \approx 3$, the assumption of an oblate atmosphere symmetrical about the Earth's axis may be over-simple, and there is the possibility of a significant contribution to equation (11) from the asymmetry produced by the day-to-night variation in air density. If f denotes the ratio of maximum daytime density to minimum night-time density, $F = (f - 1)/(f + 1)$, and ϕ_p is the Sun-perigee angle (or, strictly, the

geocentric angle between perigee and the daytime density maximum), the effect of the day-to-night density variation may be expressed in terms of the parameter μ defined by $\mu = (F \cos \phi_p)/(1 + F \cos \phi_p)$. To take account of this effect, it is necessary to add an extra term,

$$-\frac{\mu}{z}\left(1 + \frac{3}{2z}\right) ,$$

within the brackets in equation (11). This term was found to be appreciable for the last two values of H_1 in Fig 9, and was taken into account in their calculation. It is not significant for the previous value, for which $\phi_p \approx 90°$, nor for earlier values, when z is much larger. With this correction it is hoped that an accuracy of 3% in H_1 has been maintained.

The perigee height y_p is obtained by subtracting the local Earth radius from $a(1 - e)$, and the height y_1 at which H_1 applies (shown in Fig 9) is taken as $y_p + \frac{3}{2}H_p$, where H_p is determined as described in the next section. (The small correction to y_p , dependent on ω , has not been applied because greater errors in y_1 arise from errors in H_p.)

The evaluation of H has not been continued beyond 20 April, because the increased importance of the oblateness and day-to-night terms would prevent the 3% accuracy being maintained. (To be specific, the ε' term in equation (11) has a value of 0.13 for the last point in Fig 9, and would have a value of 0.3 for the next (uncalculated) point; and ε' may have errors of 10-20% in the geomagnetically disturbed week of 21-27 April.) Values of H for 21 April-3 May from satellite orbit analysis can be found in Ref 10.

5.2 Comparisons with CIRA values

The COSPAR International Reference Atmosphere 1972[11] has been widely used as a standard for comparison in recent years and has proved quite reliable, apart from some deficiencies in the representation of the semi-annual and geomagnetic effects[12]. Except for a few results from 1958-9 at only one height, CIRA 1972 was based on the mass of results obtained during the 1960s, when the solar activity index $S_{10.7}$ never exceeded 180, in the usual units (10^{-22} W m^{-2} Hz^{-1}). During the lifetime of 1980-43A, the values of $S_{10.7}$, which are shown in Fig 9, averaged about 220 with three week-long excursions above 250. Thus 1980-43A provides a test of CIRA 1972 outside its normal range.

The main Tables of CIRA give values of density and density scale height for heights of 110 to 2000 km for a series of values of exospheric temperature T_∞. Seven parameters are required in order to calculate T_∞:

(1) the 3-monthly averaged value of $S_{10.7}$;

(2) the current value of $S_{10.7}$, given in Fig 9;

(3) the current value of the geomagnetic planetary index Ap, also given in Fig 9;

(4) the semi-annual variation, specified in graphs and tables in CIRA as a function of day-of-the-year;

(5) - (7) the local time, latitude and season appropriate to perigee; these have been calculated from the orbital elements.

From the values of T_∞ thus obtained (they range between 1200 and 1420K), we find the CIRA value of density scale height H_p at perigee height y_p. This value of H_p leads to a value of $y_1 = y_p + \frac{3}{4}H_p$ and the CIRA value of H_1 at height y_1 can then be found. The CIRA H_1 values are shown as a broken-line histogram at the bottom of Fig 9.

It is obvious from Fig 9 that the values of H_1 obtained from analysis of 1980-43A are significantly higher than the CIRA values; it is also clear that the discrepancy becomes smaller as time goes on, presumably as a result of the decrease in height from 370 km initially to 282 km at the last point.

For the first five points ($y_1 \geqslant 339$ km) the values of H_1 from 1980-43A are on average 18% higher than the CIRA values, a margin that greatly exceeds the expected 3% error in the former. For the other five points, at heights of 280-320 km, the difference is less, 12% on average, but still highly significant. So it seems that the values of density scale height obtained from CIRA 1972 for heights of 280-370 km are considerably too low when the solar activity index $S_{10.7}$ is at levels near 220.

It could be argued that, since the CIRA values of H appear to be too low, the value of H_p used in calculating y_1 should also be increased by 12-18%. This would increase y_1 and reduce the discrepancy, which would become 10-16% rather than 12-18%.

The significance of the results is discussed in section 6.3

6 DISCUSSION OF THE RESULTS

6.1 Zonal winds from analysis of inclination

The orbit of 1980-43A was particularly suitable for determining zonal winds from analysis of inclination, first because the initial period was high (100 minutes) and second because the orbit was nearly polar, thus leading to the

greatest possible change in inclination (in fact nearly 0.09°) and also ensuring that any uncertainty created by the effects of meridional winds was negligible. There was only one resonance (15th order) with an appreciable effect, and that was accurately calculated (Fig 5). The resulting variation of inclination with time (Figs 4 and 6) yields two values of atmospheric rotation rate that should be completely reliable, namely:

$\Lambda = 1.10 \pm 0.10$ at height 300 km, average local time, average season;

$\Lambda = 1.15 \pm 0.06$ at height 225 km, evening and average season.

These values, which imply west-to-east winds of 40 ± 40 m/s and 60 ± 24 m/s respectively, have already been used in a recent review of upper-atmosphere winds[6].

6.2 Analysis of right ascension

The effect of atmospheric rotation on right ascension has long been known on theoretical grounds[13], and indeed was calculated as amounting to 0.04° for Sputnik 2. This was very much smaller than the change in right ascension due to the gravitational effect of the earth's flattening, which was more than 500°, so atmospheric rotation did not need to be taken into account when using Sputnik 2 for determining the even zonal harmonics in the earth's gravitational field. The effect of atmospheric rotation on right ascension did not need to be taken into account subsequently, because no other satellite of such high drag as Sputnik 2 has been used in studies of gravitational field.

The actual change in right ascension produced by atmospheric rotation has not previously been analysed, because equation (4) shows that a successful analysis could only be made if several diverse conditions were satisfied:

(a) The drag must be very severe, so that a large change in period ΔT could build up quickly.

(b) The value of $\sin 2\omega$ has to remain large and of the same sign, which usually means that the time scale should not be more than a week or two.

(c) The orbit must not be too nearly circular - otherwise I_2/I_0 will be very small.

There are two other obvious conditions:

(d) The orbit must be accurately determined.

(e) The perturbations due to even zonal harmonics must be accurately removed - a difficult task, since they can amount to 30° or more unless the orbit is near-polar.

All of these five criteria are unlikely to be fulfilled together, but they are nearly satisfied by 1980-43A during its last week in orbit; its near-polar orbit reduces the gravitational effect to only a few degrees and the main weakness is the low eccentricity - a higher value would have given a larger change and better results.

The total theoretical change in right ascension for 1980-43A during its last 8 days is 0.0028° and, as Fig 7 shows, theory and observation are in excellent agreement, thus clearly demonstrating the effect for the first time, confirming the theory and validating the standard deviations of the observational values.

6.3 Density scale height from analysis of perigee height

It is not possible to calculate the air density from analysis of 1980-43A, because its mass and cross-sectional area are not accurately known and the cross section may vary. But it is feasible to calculate the density scale height H from the decrease in perigee height because this does not depend on either the value or the constancy of the mass/area ratio. Previous determinations of density scale height from satellite orbits (eg Refs 9 and 14) have given values which are on average within 4% of those obtained from the COSPAR International Reference Atmosphere, CIRA 1972.

The values of H from analysis of 1980-43A, which should be accurate to about 3%, are much higher than those given by CIRA 1972 - 18% higher on average for the first five points at heights above 335 km, and 12% higher on average for the last five points at heights of 280-320 km. We conclude that CIRA 1972 seriously underestimates the density scale height at these high levels of solar activity ($S_{10.7} \simeq 220$) at heights of 280-370 km.

This result is not too surprising because CIRA 1972 is known to underestimate the effect of strong transient solar disturbances. Consistently high levels of solar activity ($S_{10.7} > 200$) had not occurred since 1958 and CIRA 1972 contains very little data from this era. Since the density scale height is proportional to the temperature divided by the molecular weight, it is probable that the exospheric temperature T_∞ is higher than indicated by CIRA 1972. (A lower molecular weight is less likely, because increased temperature generally goes with a higher molecular weight).

The density scale height H is inversely proportional to the height gradient of density ρ, being defined by the equation $d\rho/dy = -\rho/H$, where y is height; so lower values of H imply a faster decrease in ρ as height

increases. Therefore it is to be expected that the low values of H in CIRA 1972 will lead to low values of density at these levels of solar activity. This expectation is confirmed, though not conclusively, by the value of density obtained from the orbit of Sputnik 1 in October 1957 when the monthly-averaged $S_{10.7}$ was 281. The value of density from Sputnik 1, as recently revised[15], is $(1.7 \pm 0.2) \times 10^{-10}$ kg/m^3 at 247 km, whereas CIRA 1972 (with $T_\infty = 1500$ K) gives 1.4×10^{-10} kg/m^3. An increase of T_∞ to 1800 K would give 1.7×10^{-10}.

So we may tentatively conclude that:

(a) the density, as well as the density scale height, is probably too low in CIRA 1972 at heights of 280-370 km when the solar activity index $S_{10.7}$ is at levels exceeding 200.

To this conclusion may be added three others, also tentative:

(b) The discrepancy, being less towards the end of the life of 1980-43A, probably decreases as height decreases from 370 to 280 km.

(c) The CIRA scale heights and densities are probably too low over a wider range of heights, 250-500 km, when $S_{10.7}$ exceeds 200.

(d) The discrepancy probably increases as solar activity increases.

These conclusions are also in accord with the comparison[15] between CIRA and the values of scale height for early 1958, obtained from Sputnik 2, Explorer 1 and Explorer 3.

If the results obtained here for 1980-81 are accepted, the density scale height in CIRA 1972 should be about 15% higher for $S_{10.7} \approx 220$, and this amendment might be made by taking a value of exospheric temperature substantially higher than recommended in CIRA 1972. A 14% increase in T_∞, from 1400 K to 1600 K, increases the density scale height by 9%, for a height of 300 km, so an increase of more than 200 K seems to be required. In CIRA 1972 the value of T_∞ is taken to vary linearly with $S_{10.7}$, but it seems that the increase is faster than linear for $S_{10.7} > 200$. Any suggested amendment can only be speculative and tentative, but an addition of 100 K at $T_\infty = 1300$ K and an addition of 200 K at $T_\infty = 1400$ K would seem to be a suitably cautious revision that might give a closer approximation to reality during the high solar activity of 1981.

The more recent MSIS model[16] appears to give higher densities than CIRA 1972 at high solar activity, though comparisons are difficult to make because the many parameters involved are differently treated in the two models and the tabulations are different.

7 CONCLUSIONS

The orbit of NOAA-B (1980-43A) has been determined at 40 epochs between October 1980 and May 1981 from about 3000 radar and optical observations, of which the majority were US Navy and NORAD observations. The average orbital accuracy, radial and cross-track, was about 100 m, with a somewhat better accuracy during the final 14 days.

The orbital inclination exhibits a decrease of nearly 0.09° due to atmospheric rotation, and its variation was successfully analysed to derive two good values of atmospheric rotation rate, namely 1.10 ± 0.10 rev/day for height 300 km (average local time and season) and 1.15 ± 0.06 rev/day for height 225 km (evening and average season). See Figs 4 and 6.

It has long been known from theory that the precession of a satellite's orbital plane should be slightly altered by the action of atmospheric rotation: but this is difficult to detect and has not previously been demonstrated. The effect is clearly apparent, however, for 1980-43A during its last 8 days in orbit, and the observed change agrees well with that predicted by theory for an atmosphere rotating at 1.15 rev/day.

Ten values of density scale height H have been determined from the decrease in the satellite's perigee height. These values, which should be accurate to about 3%, are on average 15% higher than indicated by the COSPAR International Reference Atmosphere 1972 for heights of 280-370 km, although values of H obtained from previous orbit analyses agreed well with CIRA 1972. The levels of solar activity prevailing in the years 1980-81 were higher than at any time since 1958, and it appears possible that CIRA 1972 underestimates the density scale height and the density at high levels of solar activity; very little data from 1958 is included in CIRA 1972, so this result is not surprising. Suggestions are made for modifying CIRA 1972.

The satellite NOAA-B was regarded by NASA as a complete failure because it entered a wrong orbit. Tracking by NASA ceased soon after launch and NOAA-B never fulfilled its intended role of supplying weather pictures to the world. But it has instead now given some unique and useful information on the rotation rate, density and temperature of the upper atmosphere at a time when solar activity was higher than at any time in the previous 20 years. So NOAA-B did succeed in giving a picture of the atmosphere, though at higher levels than intended.

Acknowledgment

We thank Doreen Walker for assistance with the orbit determinations.

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Table 2

ORBITAL PARAMETERS FOR NOAA-B AT 40 EPOCHS, WITH STANDARD DEVIATIONS

MJD	Date	a	e	i	Ω	ω	M_0	M_1	M_2	M_3	M_4	M_5	ε	N	D	a(1 − e)
1 44524	1980 Oct 12	7121.155 1	0.06682 2	92.2121 12	141.2049 9	348.36 2	73.59 3	5202.622 2	0.7883 8	0.0011 1	−0.00118 5	-	0.68	39	7.9	6645.32
2 44533	" Oct 21	7109.404 1	0.06476 1	92.2102 7	143.5852 7	317.40 1	157.75 1	5215.532 1	0.6574 5	−0.0033 1	−0.00037 4	-	0.65	91	7.1	6649.00
3 44541	" Oct 29	7101.406 2	0.06353 1	92.2051 16	145.7099 12	289.62 2	160.33 2	5224.349 2	0.4530 9	0.0049 5	-	-	0.63	65	4.6	6650.25
4 44548	" Nov 5	7094.612 <1	0.06264 1	92.2027 14	147.5721 10	265.17 2	36.65 2	5231.857 <1	0.5435 3	-	-	-	0.56	72	5.6	6650.21
5 44554	" Nov 11	7088.653 1	0.06203 1	92.2012 10	149.1725 8	244.13 1	127.85 1	5238.458 1	0.5846 6	0.0063 2	-	-	0.52	96	5.2	6648.94
6 44562	" Nov 19	7079.519 <1	0.06134 1	92.2008 9	151.3109 8	216.11 1	316.22 1	5248.605 <1	0.6138 3	−0.0013 <1	0.00057 1	-	0.60	97	9.7	6645.26
7 44571	" Nov 28	7068.136 1	0.06056 3	92.1985 15	153.7247 13	184.65 1	87.32 1	5261.294 1	0.8103 6	-	-	-	0.84	74	4.7	6640.09
8 44577	" Dec 4	7059.328 1	0.05996 2	92.1976 12	155.3426 12	163.71 1	4.29 1	5271.148 1	0.8771 10	0.0019 2	−0.00206 11	-	0.86	62	6.2	6636.05
9 44584	" Dec 11	7049.108 1	0.05923 2	92.1967 14	157.2344 11	139.38 2	223.27 2	5282.620 1	0.7987 10	0.0093 2	0.00131 10	-	0.92	66	6.0	6631.59
10 44590	" Dec 17	7040.269 1	0.05854 1	92.1923 14	158.8631 9	118.57 2	268.84 2	5292.576 1	0.7884 11	−0.0096 5	-	-	0.67	40	4.1	6628.13
11 44597	" Dec 24	7030.668 2	0.05758 1	92.1925 20	160.7703 20	94.30 3	275.04 3	5303.425 2	0.6765 4	−0.0136 3	-	-	0.91	36	5.8	6625.84
12 44603	" Dec 30	7024.082 2	0.05673 1	92.1938 24	162.4102 14	73.57 3	77.58 3	5310.890 2	0.6472 7	0.0072 4	-	-	0.99	37	5.1	6625.61
13 44611	1981 Jan 7	7014.932 1	0.05527 2	92.1945 16	164.6077 10	45.80 2	126.97 2	5321.288 1	0.5652 9	−0.0019 2	0.00088 11	-	0.88	56	5.7	6627.22
14 44618	" Jan 14	7007.421 3	0.05385 2	92.1936 15	166.5350 10	21.16 1	324.57 1	5329.849 3	0.6299 15	0.0055 16	0.00128 24	−0.00091 18	0.80	62	5.1	6630.07
15 44626	" Jan 22	6998.691 1	0.05205 2	92.1936 14	168.7486 9	352.65 1	163.42 1	5339.828 1	0.5818 6	−0.0132 6	-	-	0.53	50	3.6	6634.41
16 44633	" Jan 29	6990.931 2	0.05057 2	92.1902 21	170.6895 12	327.15 2	131.75 2	5348.726 2	0.9015 24	0.0129 19	-	-	0.66	39	3.0	6637.40
17 44641	" Feb 6	6979.972 2	0.04880 1	92.1914 12	172.9212 8	297.67 2	136.18 2	5361.332 2	0.7899 9	0.0415 10	−0.00381 14	−0.00206 9	0.53	63	6.1	6639.35
18 44648	" Feb 13	6971.183 1	0.04761 1	92.1903 19	174.8831 12	271.67 3	263.19 3	5371.479 2	0.6928 7	0.0059 5	-	-	0.73	65	4.6	6639.28
19 44653	" Feb 18	6964.757 1	0.04682 1	92.1913 9	176.2885 6	253.04 2	138.99 2	5378.918 1	0.8114 11	0.0095 3	0.00117 22	-	0.45	63	4.5	6638.67
20 44661	" Feb 26	6950.684 2	0.04539 2	92.1928 15	178.5461 9	223.36 2	30.66 2	5395.269 2	1.3113 10	0.0139 12	-	-	0.48	44	3.0	6635.19

Table 2 (concluded)

	MJD	Date	a	e	i	Ω	ω	M_0	M_1	M_2	M_3	M_4	M_5	ε	N	D	a(1 − e)
21	44675	1981 Mar 12	6909.667 1	0.04155 1	92.1882 10	182.5449 7	171.10 1	276.96 1	5443.403 1	2.1065 11	0.0147 8	−0.00271 39	–	0.39	60	3.6	6622.57
22	44684	" Mar 21	6876.516 1	0.03825 3	92.1891 20	185.1666 21	137.39 4	127.57 3	5482.831 2	2.0087 18	−0.0127 2	−0.00108 18	–	1.08	48	6.2	6613.49
23	44690	" Mar 27	6855.782 3	0.03606 1	92.1848 14	186.9287 11	114.57 4	336.11 3	5507.734 4	2.2866 26	−0.0664 31	0.00205 75	0.00815 59	1.02	57	4.2	6608.56
24	44695	" Apr 1	6835.549 3	0.03377 2	92.1855 19	188.4124 21	95.46 6	213.25 6	5532.216 3	2.6891 27	−0.0201 13	−0.00971 43	0.00264 15	1.36	61	6.0	6604.71
25	44702	" Apr 8	6805.252 2	0.03023 1	92.1792 16	190.5168 16	68.91 5	186.02 5	5569.219 3	2.9252 27	0.0352 6	−0.00970 46	–	0.97	48	5.0	6599.53
26	44710	" Apr 16	6758.470 3	0.02426 2	92.1740 18	192.9558 17	38.65 7	312.31 6	5627.170 3	3.9757 64	0.1675 14	0.06405 212	−0.02076 53	1.18	52	4.5	6594.51
27	44714	" Apr 20	6729.683 2	0.02080 1	92.1698 10	194.1948 11	23.13 4	212.37 4	5663.333 3	4.610 6	–	–	–	0.78	79	1.29	6589.71
28	44715	" Apr 21	6722.265 4	0.01983 1	92.1704 6	194.5089 6	19.37 2	119.96 2	5672.714 5	4.732 9	−0.515 36	–	–	0.48	100	0.90	6588.96
29	44716	" Apr 22	6714.859 2	0.01896 <1	92.1685 5	194.8235 4	15.24 2	37.37 2	5682.106 3	4.946 6	0.683 14	–	–	0.35	100	0.95	6587.55
30	44717	" Apr 23	6707.015 3	0.01804 1	92.1669 5	195.1378 4	11.23 2	324.36 2	5692.081 4	4.957 8	−0.560 25	–	–	0.46	100	0.95	6586.02
31	44718	" Apr 24	6699.116 3	0.01712 1	92.1618 4	195.4537 4	7.18 2	261.25 2	5702.156 4	4.453 15	−0.578 28	2.287 83	–	0.40	100	0.95	6584.43
32	44719	" Apr 25	6691.057 4	0.01617 1	92.1632 5	195.7695 5	2.87 2	208.60 2	5712.466 5	5.239 17	0.605 30	0.920 80	–	0.47	100	0.97	6582.86
33	44720	" Apr 26	6682.186 3	0.01515 1	92.1592 4	196.0896 5	358.70 3	166.66 3	5723.852 4	6.600 20	−0.133 18	−2.283 75	–	0.35	87	0.99	6580.95
34	44721	" Apr 27	6672.069 3	0.01407 1	92.1588 6	196.4101 4	354.11 3	137.07 3	5736.881 4	6.800 26	−0.072 17	1.825 90	–	0.43	100	0.99	6578.19
35	44722	" Apr 28	6660.668 3	0.01284 1	92.1586 4	196.7311 4	349.79 2	121.37 2	5751.624 4	8.161 24	0.445 39	−3.545 159	–	0.35	100	0.82	6575.15
36	44723	" Apr 29	6648.824 6	0.01165 <1	92.1543 7	197.0545 4	345.11 2	120.93 1	5767.008 8	7.617 26	−1.030 42	2.157 142	–	0.30	75	0.82	6571.37
37	44724	" Apr 30	6635.221 7	0.01029 2	92.1540 10	197.3782 9	340.37 8	136.89 8	5784.760 9	10.036 17	1.650 43	–	–	0.43	46	0.92	6566.94
38	44725	" May 1	6618.452 7	0.00885 1	92.1494 9	197.7044 6	333.91 10	174.40 10	5806.771 9	12.476 13	0.371 43	–	–	0.47	59	0.92	6559.88
39	44726	" May 2	6594.287 6	0.00685 1	92.1439 7	198.0353 6	328.01 7	236.95 7	5838.734 8	20.766 34	−0.943 135	1.355 172	11.055 578	0.59	100	0.87	6549.12
40	44727	" May 3	6536.117 42	0.00306 1	92.1307 16	198.3722 11	314.77 27	353.34 27	5916.892 57	85.409 300	46.350 474	–	–	1.12	100	0.40	6516.12

REFERENCES

No.	Author	Title, etc
1	D.G. King-Hele J.A. Pilkington H. Hiller D.M.C. Walker	The RAE table of Earth satellites, 1957-1980. Macmillan Press, London (1981)
2	R.H. Gooding	The evolution of the PROP 6 orbit determination program, and related topics. RAE Technical Report 74164 (1974)
3	D.W. Scott	ORES: a computer program for analysis of residuals from PROP. RAE Technical Report 69163 (1969)
4	G.E. Cook	Basic theory for PROD, a program for computing the development of satellite orbits. Celestial Mechanics, 7, 301-314 (1973) RAE Technical Report 71007 (1971)
5	P. Moore D. Holland	Analysis of the orbital inclination of HEOS 2 second-stage rocket 1972-05B. Journ. Brit. Interplan. Soc., 35, 368-379 (1982)
6	D.G. King-Hele D.M.C. Walker	Upper-atmosphere zonal winds from satellite orbit analysis. RAE Technical Report 82126 (1982)
7	D.G. King-Hele D.M.C. Walker	Evaluation of 15th-order harmonics in the geopotential from analysis of satellite orbits. Proc. R. Soc. Lond. A379, 247-288 (1982) RAE Technical Report 81006 (1981)
8	D.G. King-Hele	Theory of satellite orbits in an atmosphere. Butterworths, London (1964)
9	D.M.C. Walker	Cosmos 462 (1971-106A): orbit determination and analysis. Phil. Trans. Roy. Soc. A292, 473-512 (1979) RAE Technical Report 78089 (1978)
10	D.G. King-Hele	Analysis of the orbit of Cosmos 482 in its last 15 days. RAE Technical Report (to be issued)

REFERENCES (concluded)

No.	Author	Title, etc
11	-	CIRA 1972 (COSPAR International Reference Atmosphere 1972). Akademie-Verlag, Berlin (1972)
12	D.M.C. Walker	Variations in air density from January 1972 to April 1975 at heights near 200 km. Planet. Space Sci., 26, 291-309 (1978) RAE Technical Report 77078 (1977)
13	G.E. Cook	Rotation of the orbital plane of an Earth satellite due to the atmosphere. RAE Technical Memorandum GW 351 (1959)
14	H. Hiller	The orbit of 1972-05B in its final phase, with geophysical inferences. Planet. Space Sci., 29, 579-588 (1981) RAE Technical Report 80119 (1980)
15	D.G. King-Hele	Geophysical researches with the orbits of the first satellites. Geophys. J. Roy. Ast. Soc. (in press)
16	A.E. Hedin and others	A global thermospheric model based on mass spectrometer and incoherent scatter data, MSIS. J. Geophys. Res., 82, 2139-2156 (1977)

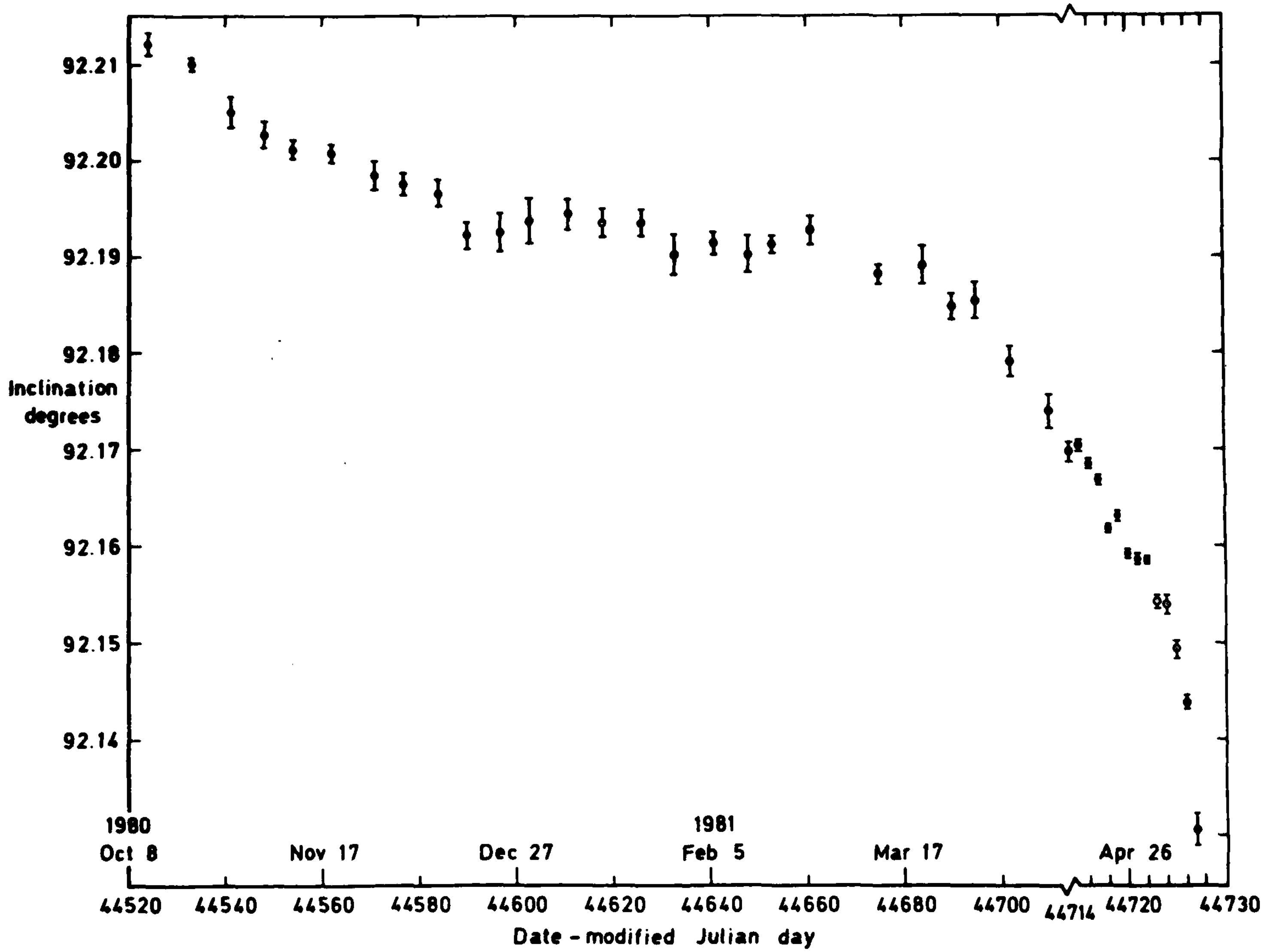

Fig 1 Values of inclination from Table 2

Fig 1

Fig 2

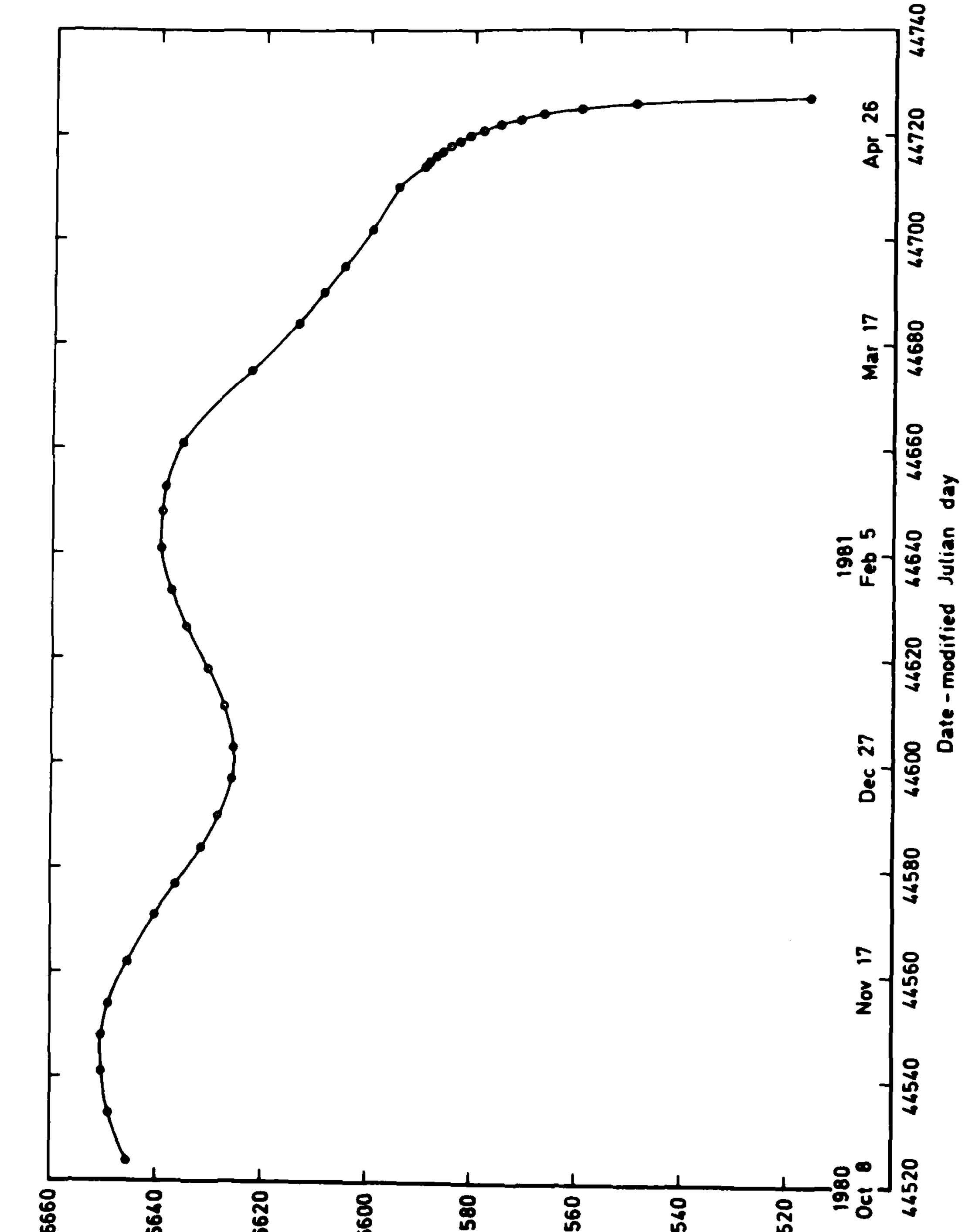

Fig 2 Values of perigee distance, a(l—e), from Table 2

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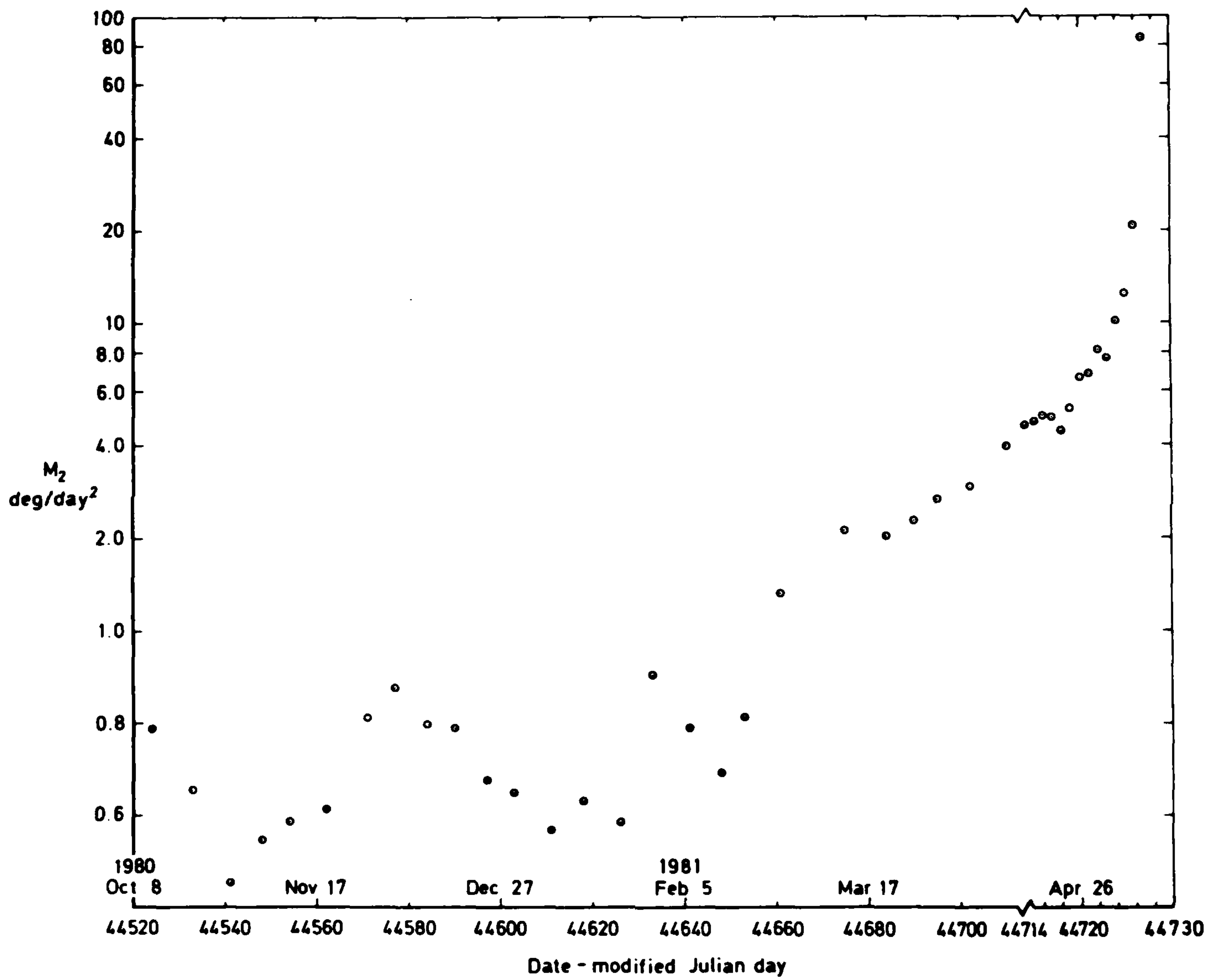

Fig 3 Values of orbital decay rate, M_2, from Table 2

Fig 4

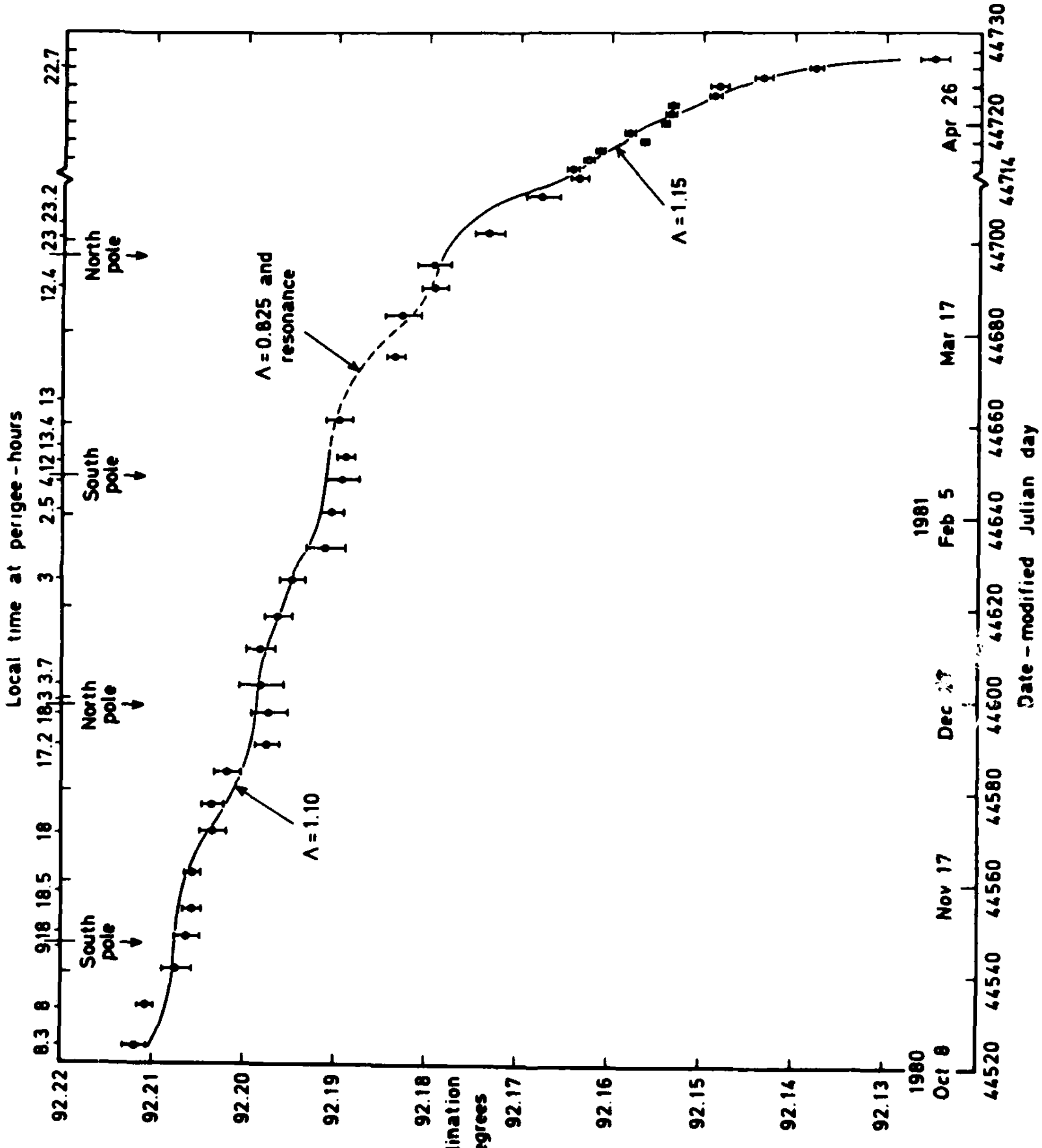

Fig 4 Values of inclination after removal of perturbations, with theoretical curves for rotation rate Λ

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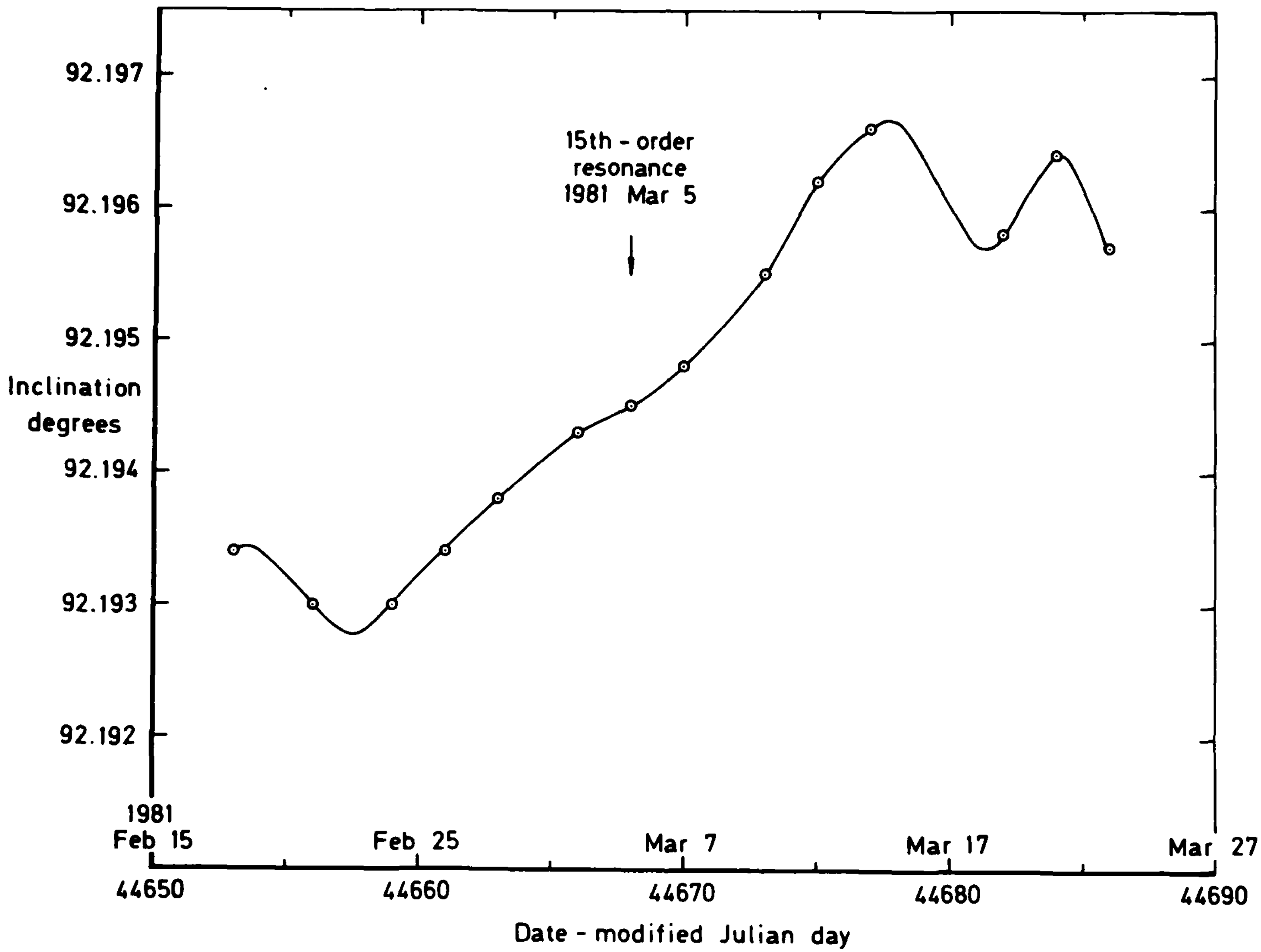

Fig 5 Calculated variation of inclination due to 15th-order resonance

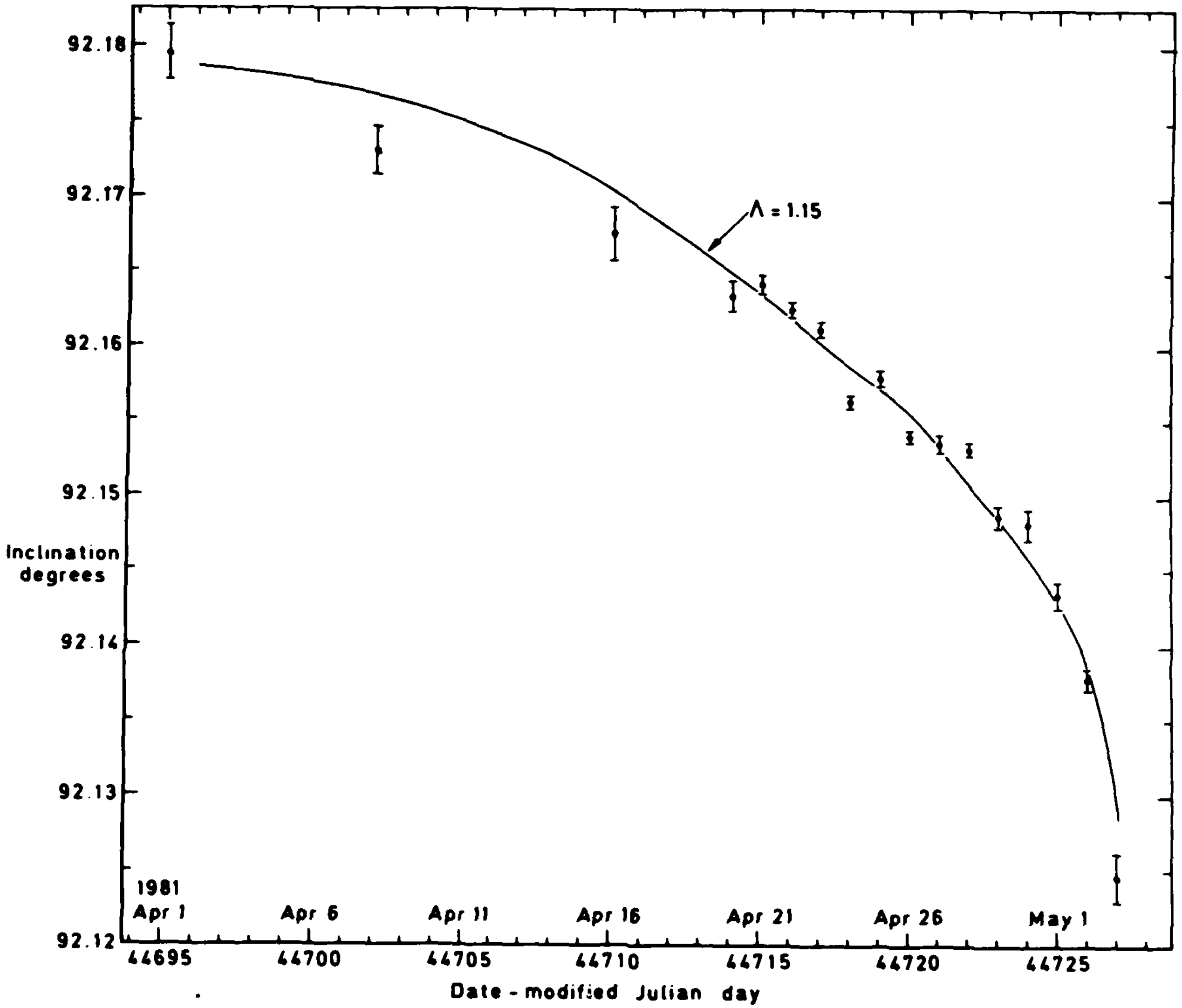

Fig 6 Values of inclination after removal of perturbations in the last 32 days of the life

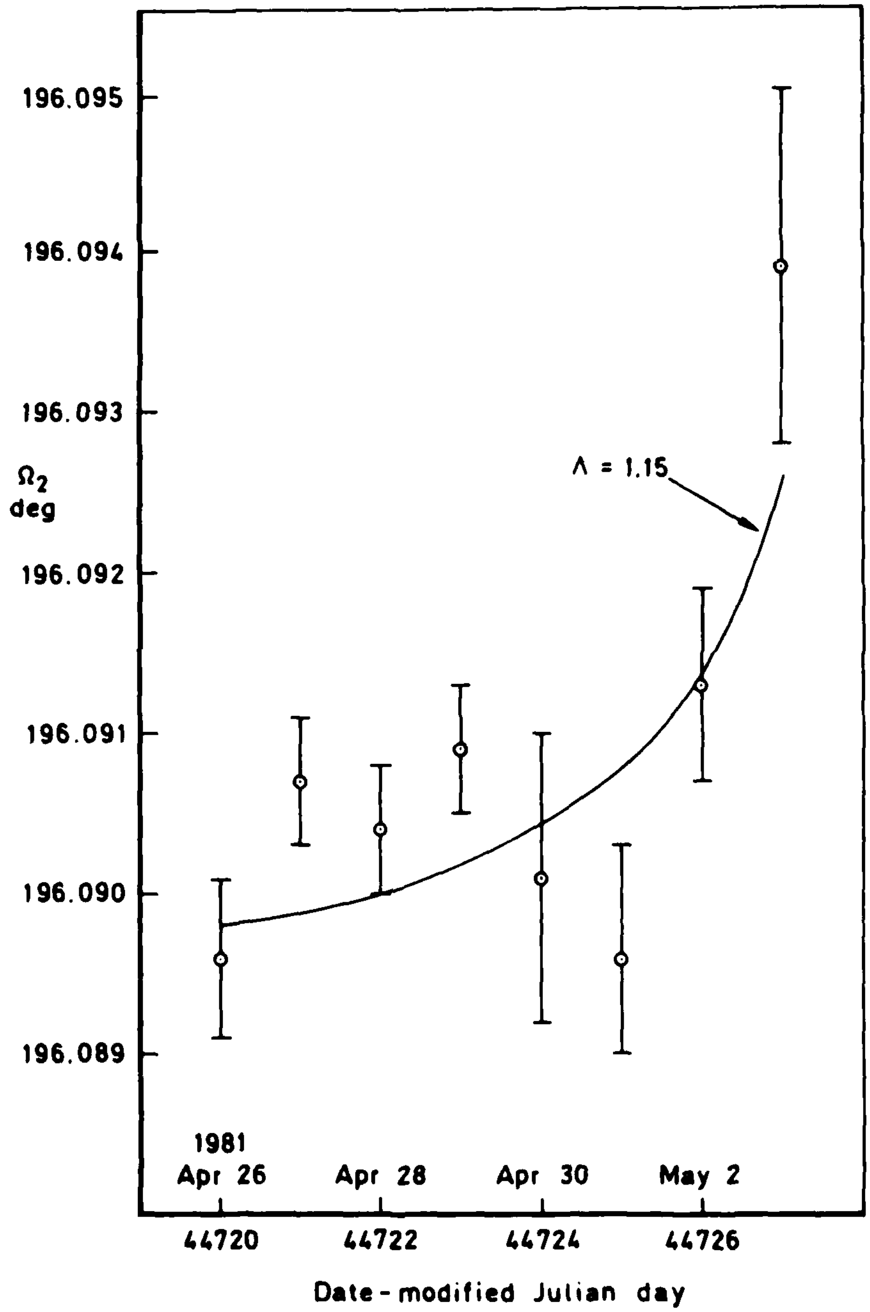

Fig 7 Values of Ω cleared of zonal harmonic and lunisolar perturbations, with theoretical variation for Λ = 1.15

Fig 8

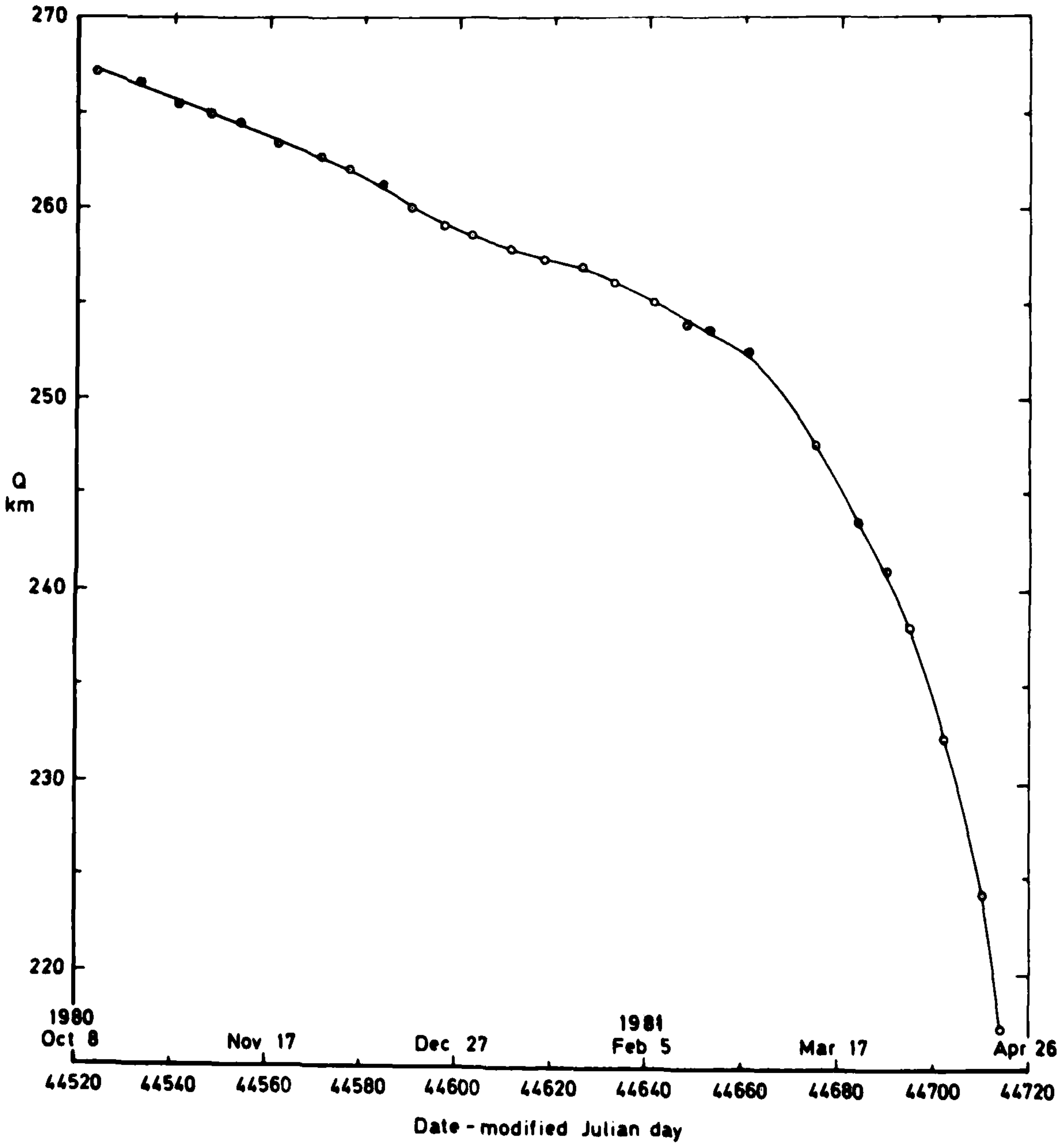

Fig 8 Perigee height over 'Earth' of radius 6387 km, after removal of gravitational perturbations

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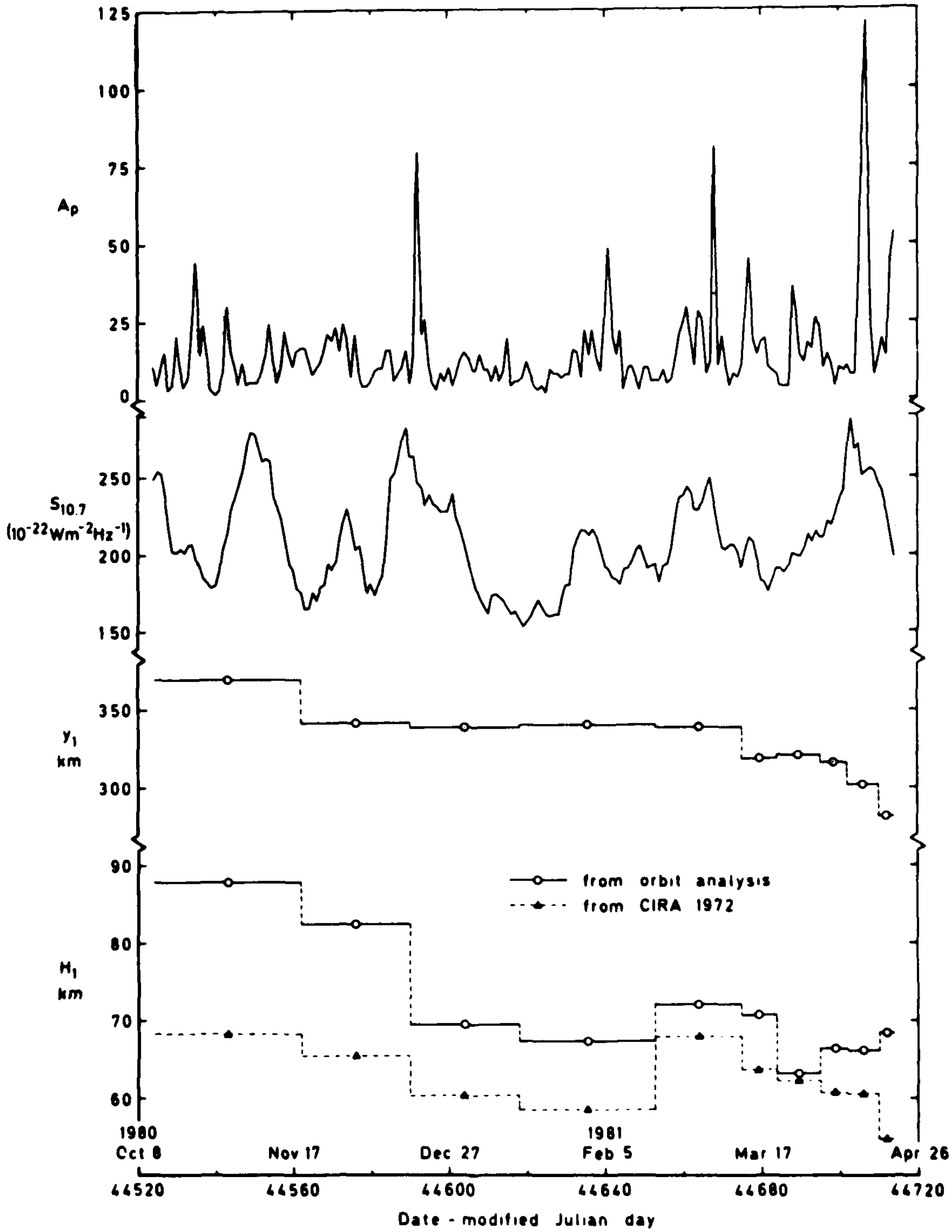

Fig 9 Values obtained for density scale height H_1 at height y_1 with CIRA values for comparison, and solar and geomagnetic indices above

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1. [illegible]	2. [illegible]	3. [illegible]	4. Report Security Classification/Marking
[illegible]	[illegible]	N/A	UNCLASSIFIED

5. [illegible]	6. [illegible] Name and Location
[illegible]	Royal Aircraft Establishment, Farnborough, Hants, UK
5a. Sponsoring Agency's Code	6a. Sponsoring Agency (Contract Authority) Name and Location
N/A	N/A

7. Title

[illegible] by the orbit of 1980-43A

7a. [illegible]

7b. [illegible]

8. [illegible]

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